SYNOPSIS OF RESEARCH PROJECT

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5.	**Major Subject**	**:**	Farm Machinery and Power Engineering
6.	**Minor Subject**	**:**	Renewable Energy Engineering
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8.	**Title of Research Project**	**:**	**DEVELOPMENT AND PERFORMANCE EVALUTION OF REAL TIME VARIABLE RATE LIQUID APPLICATOR FOR THE COTTON CROP**

9. Introduction

9.1 General

During the cotton season 2024-25 is expected to be concentrated among by a handful of countries. In terms of cotton production China was the leading producer of cotton with an estimated production of 32 million bales followed by India with approximately 24 million. In 2022-23, Brazil produced nearly 17 million bales as compared to the United States which produced approximately 14.41 million bales. Australia contributed comparatively less of about 5.6 million bales. All these major important of cotton-producing countries mostly supplying sustainability to world cotton output, thereby establishing their promoting in the international cotton sectors (Anonymous, 2025a). In 2021-22 season India had cotton planting of 123.72 lakh

hectares ranking 1.85 below the 129.27 lakh hectares in 2022-23 season. Although India recorded a fall in cotton production, the 2022-23 cotton production was at 325.22 lakh bales (170 kg each). India recorded a contraction of 3.38 percent in cotton production in comparison to 336.60 lakh bales in 2022- 23 season. India experienced a slight decrease in the cotton yield per unit of land that was at 443 kg per ha. Gujarat, Maharashtra and Telangana were the states that controlled the cotton production in India. Maharashtra was leading in terms of cotton production averaging 41.82 lakh hectares with a production of 338 lakh bales of cotton. Gujarat emerged as the leading cotton producer by yielding 87.95 lakh bales of cotton using 24.84 lakh hectares of land hence emerged as a high yield per unit of land. Telangana recorded an equal performance in the cotton production when it produced 57.45 lakh bales of cotton with a land cover of 19.73 lakh hectares of land. In India, cotton is cultivated by a small number of leading states, with which they cover a significant part of the total number of areas and output (Anonymous, 2023b). The crop (Gossypium hirsutum L.) is commonly referred to as white gold due to the significance of the crop in the textile industry. Despite the fact that India is taking a huge percentage on the cotton area all over the world, its production remains below the average of the rest of the world. This is largely explained by a number of practical challenges in the field level (Arora, 2023). Based on the field experience it may be observed that cotton is vulnerable to a lot of factors including irregular rainfall, high temperatures, soil salinity and weed infestation. There is also a visible reduction in the yield as a result of pest issues especially the pink bollworm and sucking pests. In combination with this, inadequate nutrition, in particular, deficiency of nitrogen, affects the development of bolls and their quality. Most farmers are small holders and this means that the operations such as weeding and applying fertilisers will be an added burden. Hence, to enhance a sustainable approach to cotton production, the management practices are to be improved and made more appropriate (Verma *et al*., 2024).

9.2 Agronomic Strategies for Optimizing Nitrogen Use Efficiency

Lack of nitrogen is a significant phenomenon in cotton culture that subsequently has a significant impact on the development of canopies, the formation of the boll, the quality of the fibers, and the overall productivity. We observe that the major symptoms of deficiency include pale chlorotic leaves, shortening in the internode distance, retarded plant growth, and premature senescence that consequently result in huge losses in yield (Anonymous., 2023b). also we find that poor and excessive nitrogen

management that involves under and over application does not augur well with crop. When the level of nitrogen is low, it leads to reduced vegetative growth, slows down and reduces the pod set reproductive development. We also find out that excesses of nitrogen lead to excessive vegetative growth rather than reproductive organs, retardation of maturity and rise in lodging, pest problems and pod losses (Zhai *et al*., 2010). Integrated agronomic approach to nitrogen management that involves soil testing, split application, stage-based crop growth recommendations, irrigation management and real time canopy and stress analysis benefits. The practices subsequently enhance Nitrogen Use Efficiency (NUE) that subsequently experiences enhanced uptake in crops and less loss through volatilization, leaching and denitrification hence we have the route to sustainable cotton production.

9.3 Sensor-Based Approaches for Nitrogen Monitoring in Cotton

Deficiency of nitrogen in cotton still remains one of the main limiting factors that influence vegetative growth, boll setting and fiber quality that in the long-term will eventually led to yield when they are not addressed in time. Agricultural fertilizer systems based on uniform application usually led to imbalance and hence environmental hazards as well as inefficient use of nutrients (Wang *et al*., 2022). Advances in sensor operating system the real-time applied of nitrogen in cotton cultivation. Sui and Thomasson (2006) reported that ultrasonic sensors are capable of estimating crop canopy height, and indicating of biomass, height and nitrogen deficiency. The studied are combination use of ultrasonic and principle of sound wave and spectral data within ground-based to plant height sensing improves the accuracy of detection of nitrogen level Such integrate supporting precision efficiency and applied fertilization strategies and accumulated to more suitable of sustainability crop production systems. thermal sensor is highly detecting are nitrogen related heat stress and calculated of canopy temperature and stomatal is the best example for crop stress result of the altered stomatal conductance. The detected of crop water stress levels using an infrared thermal sensing method was experiment by the use of a high resolution using thermal sensor reading and a basic Crop Water Stress Index (CWSI) in a study by Bian *et al*. (2019) to detecting the application of the thermal sensing received in non-contact crop measurement.

9.4 Multi Sensor-Enabled Tractor Applicator for Smart Nitrogen Delivery in Cotton

Recent advances in the field of precision agriculture have been associated with the

development of multi sensor systems on tractors that in their turn are employed in the application of liquid fertilizer to cotton (Gossypium hirsutum). We observe that these systems that assemble data of different sensors such as canopy reflectance, ultrasonic height and soil moisture are what enable real time crop variable analysis. In research by Anandraddi *et al*. (2018) we observe that indeed the sensor integrated applicator was indeed going on the go and therefore applied specific site-specific nutrients depending on the real crop requirement. Another small tractor mounted inter cultivator that also happened to be a fertilizer applicator were found to work best at 2.0km/h forward speed and 14% soil moisture which in turn resulted in uniform distribution of the fertilizers with a field efficiency of 72% and at the same time put minimum stress on the crop. In a bid to enhance the spatial resolution, Bronson *et al*. (2022) installed 75 kHz ultrasonic sensors to undertake the irrigated cotton height measurement task that produced a R2 of 0.92 when using manual measurements thereby allowing vertical zoning in the application of variable rates of nitrogen application. Additionally, Bian *et al*. (2019) employed high-res infrared thermal imaging that they put into practice to observe 2-3 degree C disparities between nitrogen deficient and healthy fertilized cotton rows which they subsequently applied an abridged version of Crop Water Stress Index (CWSI) to which in its turn they use to guide nutrient application basing on the stomatal conductance and transpiration dynamics. also report Mahan *et al*. (2014) that through the combination of ambient air temp sensors and canopy temp data we have an enhanced accuracy in the nitrogen timing in variable irrigation systems which are in turn the heat unit accumulation models. In our case of tractor with a set of sensors that comprise ultrasonic, thermal and ambient temperature has claimed up to 25% saved nitrogen as well as 30% enhanced Nitrogen Use Efficiency (NUE) and yield that is at or close to the maximum attainable which is a very sizable leap forward in the use of sensor-based automation to sustainably intensify cotton.

10. Practical Utility of the Research Project

The future of cotton crop management is the use of tractors that have boom sprayers with built-in ultrasonic and infrared (IR) thermal sensors. The ultrasonic sensors give real time information on canopy height, width and volume which in turn we utilize in variable rate application (VRA) of pesticides and fertilizers. This implies that it can only apply the correct amount of chemicals in the field in both the dense and sparse areas and as a result this minimizes over application as well as reduces pollution of the environment. Another application of IR thermal sensors, as is the case with the

canopy temperature differences and water stress, which we are able to detect using these sensors, and it can be rectify using the specific practices which lead to an enhancement of plant health which also results in an increase in yield. Through such sensors tractor mounted sprayers can deposit chemicals with high precision that consequently enhance resource efficiency and safeguard the environment as well as beyond precise application sensor aided tractor sprayers, it ensure that are able to have data driven farm management. It can observe into the automated systems where they save us on labor and time involved in the monitoring of vast cotton fields, it also notice that the sensor data that is logged gives us information into the canopy growth patterns, stress levels and treatment outcomes. That information then informs our agronomic decisions it can better assemble our fertilizer regimes and place more emphasis on our pest management plans. as well as we observe that the application of ultra sonic and IR thermal sensing will support sustainable farming practices by which we observe a drop in chemical drift, conservation of inputs and soil and water pollution. All these tech solutions offer a viable solution to the problem of cotton productivity and sustainability in farms in the present day.

11. Objectives

1. To study the existing variable rate fertilizer system
2. To design a variable rate applicator system for nitrogen deficiency in cotton crop using sensor-based application
3. To evaluate the performance of the developed liquid fertilizer applicator under laboratory conditions
4. To develop tractor mounted variable rate fertilizer applicator and its performance evaluation in the field.

12. Review of Literature

12.1 Use of Ultrasonic Sensors in Agriculture

Moltó *et al*. (2001) introduced a variable rate sprayer based on the use of ultrasonic technology; they put in to use three ultrasonic sensors for the task of measuring canopy width and in turn for the adjustment of spray output. What they reported was that the 21 use of three points of detection improved canopy measurement accuracy by 18% which in turn made flow rate decisions more reliable. The system went in to action with three spray settings (low, medium, high) which in turn enabled what they term as selective application and in that process saw a great reduction in chemical waste. In the field they reported a 35% reduction in pesticide deposition on

soil and a 25% drop in spray drift which in turn confirmed the environmental benefit of multi sensor control. Later 24 research has reported that which is which reports of studies present that we see a 20 to 40 percent savings in agrochemical use with the ultrasonic canopy sensors which we note is dependent on crop structure and terrain but at the same time that the coverage is not affected. also, it is put forth that multi sensor platforms do better in terms of detection consistency, they do a better job of reducing off target contamination and that they improve overall sprayer performance as opposed to single sensor or uniform rate systems.

Tumbo *et al*. (2002) did a study which compared laser and ultrasonic sensors for the purpose of measuring canopy volume in orchard crops. We found out that in our study which we ran at a 70% lower price point for laser-based systems the ultrasonic sensors did very well at 88% accuracy. also, we noted that we saw a 70% drop in price for the ultrasonic as opposed to the laser-based systems which made them a great choice for precision agriculture at a lower cost. But what we also saw was that in dense or very complex canopies the performance of the ultrasonic went down by 12 to 15% which we put down to issues of signal scatter and leaf interference. also we saw that the differences between what we measured with the ultrasonic and what we got from manual reference values was all over the place ranging from 82.63% to 128.71% which we think is a clear sign that we need to see better calibration practices and also the use of multiple sensors. Configurations which present a solution, or sensor fusion methods we have put in place to improve reliability and report consistent results within various crop densities.

He *et al*. (2003) reported they developed an electrostatic, air assisted orchard sprayer which they integrated with infrared (IR) sensors for the purpose of automatic canopy detection and select nozzle activation. The IR guided control system which they put in place caused spray discharge only when foliage was present which in turn a reported chemical savings of 50-75% vs. conventional continuous spray. also in the field eval they found that electrostatic charging improved spray deposition on the leaves by 28% which in turn improved coverage uniformity while at the same time drift into off target empty areas went down by as much as 60% which played to strong environmental benefits. That said the authors did report that IR sensors had detection errors greater than 15% in variable light and dense foliage which in turn limited their reliability in diverse orchard settings. it is brought to light that we require better signal processing, sensor calibration, or use of multiple sensors to maintain that which is stable in many field settings.

Solanelles *et al*.2006 which had in it an electronic sprayer that used ultrasonic leaf area sensors with proportional solenoid valves for variable rate application based 28 on real time leaf canopies width. What they reported was that the system did very well 21 which is that it achieved 90% application efficiency which in turn gave precise chemical delivery at the same time which also saw large scale reduction in over application. They reported that off target loss went down by 45% which in turn proved out the value of sensor-based control in to minimize environmental impact. also the sprayer did very well at forward speeds of 5 to 7 km/h and the electronic control unit which ran it all made for very quick response time of less than 0.3 seconds. In total what their study put forth was the success of the integration of ultrasonic sensors and proportional valve technology in to improve precision, efficiency and environmental sustainability in orchard spraying

Zhai *et al*. (2010) reported they developed a real time ultrasonic sensing platform for dynamic overhead structure measurement and precise sprayer control. They found out their system which reported very high in term of measurement reliability, achieved 92.8% in standard canopies and 90% in cherry canapes which they said is great results across different orchard settings. The ultrasonic platform they designed enabled quick actuator response, we are talking of nozzle activation within 0.2 seconds of detecting the canopy which in turn made the sprayer to very precisely time chemical release with the -- as it happens presence of leaves. In the field they evaluated this real time detection and select spraying which they reported to have chemical use reduction of up to 40% which they put forth as proof of the benefits of integrating ultrasonic sensing with automatic sprayer which in turn improved efficacy. also they presented that ultrasonic tech which they used is very much a low-cost solution for what is required in specialty crops.

Llorens *et al*. in 2010 looked at the performance of an ultrasonic which they designed 17 for variable rate application in vineyards and reported great improvements in efficiency and crop response. What they found was that by using select spray modulation total pesticide use went down by 58% which in turn proved the value of using the canopy guided application to reduce chemical input. also despite the low volume of spray the system did better then we see in conventional methods which reports a 22% increase in leaf surface coverage which in turn means better deposit on the target leaves. also, we saw that this precise approach improved vineyard productivity which in term had a 15% increase in fruit yield over conventional uniform

spray methods. The machine performed well at a travel speed of 6 km/h and also had a very quick response time of under 0.25 seconds which enabled very good sync between travel and spray delivery. Variable architecture designs. In general we saw that ultrasonic powered variable rate systems do which improve environmental sustainability while at the same time do not sacrifice or in some cases better crop performance.

Jeon and Zhu (2011) reported on a variable speed precision sprayer which they developed that used ultrasonic sensors at 20 Hz which they used to determine canopy density which in turn modified spray output in real time. The system which changed spray volumes with changes in leaf mass achieved a spray accuracy of 87% which we note is very well aligned with what was measured and what was which the sensor was putting out. also, in the field they saw that this which is a very targeted approach to spraying reduced pesticide use by 32% as compared to constant rate applications. The device also performed well at speeds of 4 to 6 km/h which is what is seen in normal orchard management practices. also, it was found that the solenoid valves which we used for flow regulation had very fast response times of below 0.3 seconds which in turn very accurately synchronized the sensor detection with spray release. As a whole the study reported on the great promise of high frequency ultrasonic sensing to improve chemical efficiency and also the precision of application in present day orchard spraying systems. also it was found that the solenoid valves which we used for flow regulation had very fast response times of below 0.3 seconds which in turn very accurately synchronized the sensor detection with spray release.

Chen *et al*. (2002) As a whole the study reported on the great promise of high frequency ultrasonic sensing to improve chemical efficiency and also the precision of application in present day orchard spraying systems. 95%, Making them more precise then ultrasonic systems in complex canopy settings. But we saw that the device required high performance computing hardware which could process real time LiDAR data at 10 Hz which in turn increased the overall system's complexity, power demand and cost. That said the study reported that LiDAR enabled variable rate spraying does in fact greatly improve precision and environmental sustainability in perennial crop management.

Esau *et al*. (2013) introduced a vision-based sprayer which had 4 digital cameras and image processing algorithms for detection of fungal infections in blueberry leaves. They achieved a disease detection accuracy of 92% which in turn enabled

targeted fungicide application. Pesticide use was reduced by 40% but the system required a 2.5 GHz CPU and 8 GB RAM which made it out of reach for small farms.

Li *et al*. (2018) reported on a laser scanning orchid sprayer which had dynamic spray rate adjustment. Their LIDAR system they used for mapping of the canopy had a resolution of 2 cm which in turn enabled very precise deposit control. They saw a 33% improvement in spray efficiency but hardware costs out to over $8,000 USD per unit and. integration required custom software and calibration routines, limiting scalability.

Zürey *et al*. (2020) put forth a which they designed as an automatic nozzle control system that used four JSN-SR04T ultrasonic sensors, four solenoid valves and a PIC18F45K80 microcontroller for real time, selective spray delivery. The system reported very good performance at detection ranges up to 5 meters and also featured IP68 rated water proofing which in turn made for very reliable performance in outdoor agricultural settings. In the lab we saw 100% spray actuation whenever a tree canopy was detected and instant nozzle shut off when no object was present which in turn proved out the precision of the ultrasonic trigger-based control logic. The select which they presented also saw a 48% reduction in pesticide use which we can see to have environmental and economic benefits. also the total system integration cost of which they report is. Reduced 60% in comparison to LiDAR based sprayers which in turn makes it a cost-effective solution for precision orchard management.

Kaleem *et al.* (2022) study which developed a sensor integrated platform for the detection of canopy structure, Kaleem *et al* reported 92.8% accuracy for standard canopies and 90% for cherry canapes which in turn enabled nozzle activation within 0.2 seconds of detection. This very quick response in turn reported a 40% reduction in chemical waste which in turn put forth the system's value in precision spraying in orchard settings. also they looked at key issues of sound cone distortion and sensor cros talk which in turn stressed the importance of sensor calibration and proper spatial alignment. These results support the use of ultrasonic sensing in automated sprayer systems especially for small holder orchards which are in search of costeffective site specific input delivery.

Salas *et al*. (2023) A sensor-based air blast sprayer was developed by using six ultrasonic sensors and a variable-rate based Density Factor (Df). Depending on the structure of the canopy, the spray pressure was adjusted between 4.0 and 14.0 MPa. Field tests demonstrated that the application rates were accurate to within 93%. The system allows for GNSS integration to enable speed-based flow control in real-time.

By using the sprayer, the quantity of chemical used was reduced by 52% maximums and improved the deposition uniformity by 28%.

Srigiri *et al.* (2025) compared the performance of ultrasonic and infrared sensor for canopy detection. Ultrasonic sensors exhibited an error of 5.6 millimetres whereas IR sensors showed an error of 15.4 millimetres at 500 millimetres. Ultrasonic sensors had a detection range of 147.33 mm, IR sensors only 50.66 mm. Time of responses was 0.20 s and 0.25 s, respectively, for ultrasonic and IR. Ultrasonic sensors were identified as the most suitable technology to fit orchard sprayers thanks to its accuracy and speed response.

12.2 IR thermal sensors used for nitrogen stress detection.

Shimshi, D. (1970) This study examined how varying nitrogen levels affected transpiration and stomatal behaviour of bean plants (Vigna radiata L.). According to the study nitrogen availability affects stomatal activity which enhances or reduces transpiration rates and plant temperature. The supplied nitrogen will result in stomatal conductance and transpiration rates. The more cooling effect of the leaf surface. On the other hand, plants with nitrogen deficiency showed less stomatal opening, which resulted in lower transpiration rates increasing the leaf temperature. Higher leaf temperature under nitrogen deficiency indicates stress conditions and lower physiological activity. The study conclusively established that nitrogen equally influences the regulation of water (or relative humidity) relations and the surface temperature of the canopy (or leaves) through stomatal control (that is, stomatal conductance). As a result, we can use leaf or canopy temperature to indirectly assess crop nitrogen status This helps detection of stress, and nutrient management systems.

Idso, S. B *et al.* (1981) The idea that canopy temperature may be a useful indicator of crop water stress was proposed by Idso *et al*. (1981), who also introduced the Crop Water Stress Index (CWSI). The research revealed that plant transpiration can greatly affect canopy temperature, which in turn depends on stomatal conductance and plant health. With adequate water and nutrients transpiration rates are appreciable resulting in cooler canopy temperatures. Nonetheless, under stress conditions such as water deficit or nutrient deficiency (like nitrogen), stomatal closure reduces transpiration increasing canopy temperature. The researchers learned to quantify a relationship between canopy-air temperature difference and stress level of plants to enable detection of stress in real time by infrared thermometry. This research provided scientific basis of thermal sensors for use as a rapid, reliable, and non-destructive tool

to monitor crop stress for precision input management.

Bahar Bilge *et al.* (2008) investigated the effect of canopy temperature depression on grain yield and yield components of bread and durum wheat under heat stress conditions. According to the findings, CTD is a crucial crop physiological indicator where higher CTD (cooler canopy temperature) is associated with improved plant water status and transpiration rates. The findings of the study revealed that CTD has a positive association with grain yield, spike yield and number of grains per spike, indicating that cooler canopy crops yield better under stressful situations. Under high temperature stress, the canopy temperature of durum wheat genotypes was found to be relatively cooler compared to bread wheat, indicating better tolerance to heat stress in durum wheat genotypes. According to the finding, CTD can be used as a selection criterion for breeding purposes of heat- and drought-tolerant varieties as it reflects physiological efficiency and adaptability to stress.

Fisher and Huang (2017) The soybean-canopy mobile IR monitoring system in the system integrated portable IR thermometer, GPS and microcontroller and worked at a height of 1.2 meter above the canopy. Canopy temperature readings differed by 3.2°C between the irrigated and non-irrigated plots. Through real-time precision irrigation, customer expectations were seen to be met.

Sukhjeet Kaur *et al*. (2018) The research implemented as a field experiment aimed at finding the canopy temperature as an indication of thermal and nutrient stress in wheat in relation to date of sowing, nitrogen levels and post-anthesis strategies. The canopy temperature significantly reduced (by about 1-2°C) with increased nitrogen application, indicating better crop health as well as weathering. When sowing is done at early date of October 30, the canopy becomes cooler in comparison to later sowing date which will help in escaping heat stress during grain filling. Moreover, foliar treatment of $ZnSO_4$ and thiourea reduced canopy temperature by 0.5-1.0°C, relieving the stress conditions. A notable negative linear relationship was observed between canopy temperature and grain yield. A positive change of 1°C was associated with a corresponding negative change of 1.5-1.7 q/ha grain yield. According to the study, canopy temperature is a reliable non-destructive indicator of heat/cooling and nutritional stress that can be successfully employed for stress management of crops and predicting crop yield.

Chenchen *et al.* (2020) In their study, manufactured a real-time canopy temperature profiling system using IR sensors in cherry orchards. The system achieved

measurement accuracy of 92.8% with the temperature deviation of ±0.5°C for varied light. The IR sensor was placed 1.5 m above the ground and had a response time of 0.2 Seconds, making possible effective detection of canopy stress at midday. During this time, evapotranspiration reached its peak.

Pineda *et al.* (2021) Had an overview of thermal imaging uses in precision agriculture. It was reported that IR thermography can detect 2.0-3.5°C temperature increases under stress in tomato and pepper. The best imaging angle was achieved over the range 30-45°. Use of thermal indices of CWSI, Tc-Ta improved the stress classification accuracy to above 90%.

Giménez-Gallego *et al.* (2023) A low-cost thermal imaging sensor for use in pomegranate orchards under regulated deficit irrigation was tested by Comparison of the sensor and commercial IR radiometers. (13) The sensor was found to exhibit a very strong correlation with commercial IR radiometers (R^2 = 0.976). The canopy temperature was as much as 4.2°C different between the stressed and non-stressed trees. The sensor was operated at 1 frame/sec with a detection range of 0.5-2.5 m and was deployed under a shade net house.

You, C., Xu, P *et al.* (2023) Heat stress at flowering damage the photosynthetic apparatus and diminishes antioxidant capacity thus poses a serious threat to rice production. Using a mix of nitrogen (NH_4^+:NO_3^- at 50:50) reduces the detrimental effects because leaf nitrogen content is significantly increased resulting in improved net photosynthetic rate, stomatal conductance and transpiration. Subsequently, the transpiration is enhanced resulting in reduction of the temperature of panicles and leaves cooling the plant. Moreover, the activities of the main antioxidant enzymes, namely superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), were enhanced, consequently assisting the plants in reducing the accumulation of reactive oxygen species (ROS) and limiting membrane lipid peroxidation. As a result of these physiological improvements, the seed-setting rate and 1000-grain weight improve rice yield under extremely high temperatures.

Smigaj *et al.* (2024) investigated the application of UAV thermal infrared sensing in forest and orchard settings. Their research showed that canopy temperature anomalies of 2.8 °C correlated with drought stress indicators. The IR sensor of UAV at 120 m height with thermal resolution of 0.05°C and a GSD of 15 cm/pixel. It was pointed out by the authors that radiometric calibration can help reduce noise from the environment.

Min Jiang *et al.* (2024) Conducted a two-year field experiment using drones equipped with high-precision thermal cameras. They found that nitrogen fertilizer significantly reduces rice canopy temperature. Specifically, the zero-nitrogen control (CK) consistently exhibited higher temperatures compared to moderate (200 kg ha^{-1}) and high (300 kg ha^{-1}) nitrogen treatments during the tillering, jointing, booting, and heading stages

Yadav *et al.* (2024) The effect of infrared thermometer (IRT) field of view on canopy temperature and CWSI in wheat was studied. The IRT was at a height of 10 - 100 cm above the canopy with a field of view (FOV) of 51.28 – 5,128 cm^2. The canopy temperature difference was between 9.2 to 36.4% while CWSI values varied from 0.65 to 2.71% at four irrigation regimes. The slope and intercept declined by 5.7% and 20.6%, respectively, when the distance of IRT was increased.

12.3 Managing Nitrogen in Cotton

Van der Sluijs (2022) The impact of nitrogen application on fibre quality of cotton was reviewed by van der Sluijs (2022). According to the study, nitrogen application increases yield but its excessive application (>180 kg Nha-1) decreases fibre strength and micronaire with no benefit. Worldwide, nitrogen makes up 58% of fertilizer use and cotton fibre quality is sensitive to nitrogen-induced vegetative growth. The reviewers advised balancing N inputs to sustain yield and fibre integrity.

Qin *et al.* (2023) A dilution curve for critical nitrogen concentration (CNC) for cotton under straw incorporation is developed by Qin *et al*. (2023). Nitrogen treatments included 0, 60, 120, 180 and 240 kg N/ha. The calculated CNC model was y = 3.4921 (R^2 = 0.8741) while NNI (≈1.0) was optimum at 120 kg N ha^{-1} indicating the adequate nitrogen status of rice. Yield stabilized after application of 180 kg N $ha^{-1.}$

Ahmad *et al.* (2024) A long-term field trial was conducted to optimize nitrogen levels for cotton in semi-arid zone. The seed cotton yield and biomass were highest in 240-280 kg N ha^{-1} treatment with variations in the treatments of N. The nitrogen content of the leaf reached its highest level at 210 kg N ha^{-1}, and canopy height and leaf area index increased at higher nitrogen rates. The study showed that use of nitrogen in slightly excess of the recommended rate improves yield and profitability under semi-arid conditions.

Mounika *et al.* (2025) Penned an article evaluating nitrogen management in organic cotton using vermicompost. Treatment Gossypium hirsutum and G. applied was kg of N ha^{-1} and 60. arboreum. A G. produced the maximum seed cotton yield

(1508 kg ha^{-1} and stalk biomass (3685 kg ha^{-1}) at 60 kg N ha^{-1} treatment. hirsutum. The economic analysis revealed a gross return of Rs. 1,13,400 ha-1Rs. 59,400 ha-1as net return and benefit-cost ratio.

12.4 Tractors and spraying machinery

Aman *et al.* (2020) This study evaluated a tractor-operated boom type sprayer in guar fields under varying operating conditions. The sprayer used 50 cm nozzle spacing which was fitted at a height of 55 cm above the crop canopy. The test was conducted at three forward speeds (3.0, 3.5 and 4.0 km/h) and three fluid pressures (2.0, 3.0 and 4.0 kg/cm²). The droplet density was 8.86 to155.46 drops/cm². The spray deposition volume varied from 82.5 to 1201.53 × 10 -6 cc/cm 2 on upper leaf surfaces. The Relative Spray Factor (RSF) estimated on volume and number basis varies between 0.46 to 1.22 and 1.37 to 3.77 respectively indicating variation in coverage on placed leaf surfaces.

Kumar *et al.* (2021) Created a sprayer that attaches to a tractor and uses hydraulic booms. The boom, which can be adjusted from 6.0 to 9.0 m, allows coverage of a 0.45 ha/h at 4.5 km/h. The sprayer used flat fan nozzles which is operated at 2.5 kg/cm² which makes droplet size is 250-300 µm. In the field, the efficiency was determined as 87.2 per cent with a chemical saving of 22.4 per cent over the manual knapsack sprayers.

Jadhav *et al.* (2022) A tractor-operated air-assisted sprayer has been developed for orchard crops. The system comprised a centrifugal fan (600 mm diameter) which is capable of giving air at 18m/s aligned with six hollow cone nozzles. Operating at a speed of 3.2 km/h, the sprayer was found to achieve leaf coverage of 72.5 whilst droplet penetration depth of 4.8 cm in dense canopy. A decrease of 31.6% in spray drift was observed.

Manojkumar *et al.* (2023) utilized a factorial CRD system design to optimize the operational parameters of a boom sprayer. Nozzle spacing, boom height and pressure were tested by them (30 40 50 cm), (80 90 100 cm) (17 5 21 0 24 5 kg/cm2). The swath width of the tractor-operated sprayer developed at PAU is one of the most important parameters. The combination of 50 cm spacing, 90 cm height and 24.5 kg/cm2 pressure gave a swath width of 7.77 meter with 43.12% overlapping. The evaluation of the performance in terms of spray uniformity was carried out it is evident that 81 trials were carried out and the statistical analysis confirms the significant influence of these parameters on spray uniformity.

Patel *et al.* (2024) Patel *et al*. (2024) proposed a tractor-operated automatic boom sprayer equipped with section control for the implementation of GPS. Pesticide is sprayed only in the target regions using electromagnetic solenoid valves for activating nozzles, which reduced pesticide by 38 percent. The sprayer at a speed of 5.0 km/h covered an area of 0.52 ha/h with a droplet size of 280 µm. Compared to conventional boom sprayers, the system enhanced application accuracy by 26.8% and cut down labor needs by 40%.

13. Materials and Methods

13.1Location of Experiment

The study will be carried out at the Department of Farm Machinery and Power Engineering, College of Agricultural Engineering and Technology, Junagadh Agricultural University, Junagadh.

13.2 Year and Season of Experiment

The experiment is to be conducted during the academic year of 2025-2027.

13.3 Design Considerations

I. The prototype will be designed according to the minimum row spacing of the cotton crop to ensure smooth operation in the field.
II. The design should be simple, cost-effective and manufacturable using locally available materials.
III. All components should allow easy assembly and disassembly for maintenance and inspection.
IV. The design should be easily repairable while ensuring operator safety and comfort.
V. The system should allow simple operation and convenient maintenance.
VI. Development and performance evaluation of real time sensor integration variable rate liquid fertilizer for the cotton crop
VII. The system should be modular to allow future upgrades and scalability
VIII. The prototype should be weather-resilient to withstand dust, moisture and temperature variations.
IX. The system should include data logging and analysis capability for performance tracking and optimization.

13.4 Overview of the Proposed Machine

The current research involved the development of a tractor-mounted boom sprayer in the quest to enhance efficiency of application of chemicals in cotton fields.

The system has an ultrasonic sensor (HC-SR04) and an infrared thermal sensor (MLX90614) to monitor canopy and plant conditions of crops as they pass over the field. A sensor reading is then processed by a microcontroller (Arduino Uno or Raspberry Pi) which closes and opens solenoid valves and manages the rate at which liquid spray flows. This enables the chemical to be administered depending on the actual crop requirement instead of administering it in the same manner. This arrangement operated on a 12V supply and adequate mounting and protective facilities were put to provide a stable operation of the setup in the field. It was noted during the operation that the system assisted in enhancing the unnecessary use of chemicals, and it also resulted in better productivity of the entire spraying process, which in turn facilitated the management of the resource in cotton production.

The prototype development will be through computer aided design (cad) and printing of the mechanical structure and setting up of communication using distributed electronic systems. The prototype will then be tested regarding system accuracy. The test shall be conducted under different operating conditions where the initial trials would be conducted at the Department of Farm Machinery and Power Engineering, CAET, Junagadh Agricultural University, Junagadh.

13.4.1 Computer Aided Design

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test shall be conducted under different operating conditions where the initial trials would be conducted at the Department of Farm Machinery and Power Engineering, CAET, Junagadh Agricultural University, Junagadh.

13.4.2 Working Principle of the Machine

The ultrasonic sensor provides a rough estimate of the size of the canopies, and the thermal sensor shows the level of stress as higher leaves temperature in selected plants. Following these observations, it is possible to make the controller (Arduino or Raspberry Pi) react to the need and regulate the opening of the solenoid valves. Consequently, the nozzles target a required location only with the spray. This will assist in the prevention of over application and utilize more efficiently in cotton farming

13.4.3 The Machine Development.

* The design of the boom sprayer that will be operated by the tractor will incorporate building of a strong metallic frame that can fit in cotton fields, assembly of a tank and boom with adjustable nozzles and incorporation of ultrasonic and IR thermal sensors to provide real time monitoring of the canopy. Powered by electricity solenoid valves, flow meters and the microcontroller system (Arduino/Raspberry Pi) will be attached in order to spray automatically. All parts will be firmly held in place using brackets and safes enclosures to enhance durability, ease of use and stability even at the field environment.

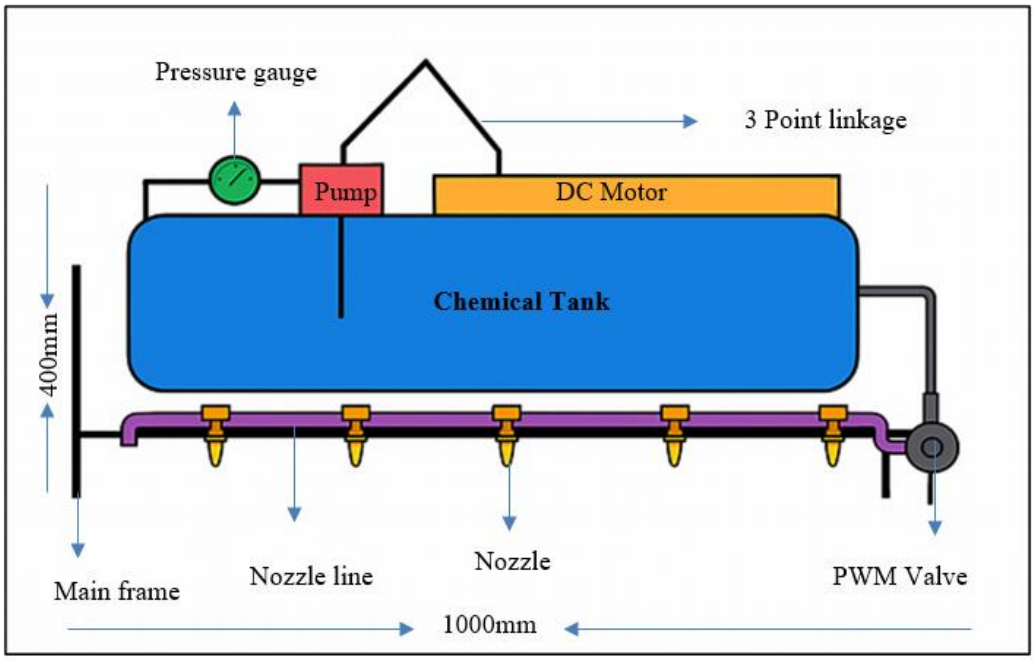

Figure 1. Conceptual View of the Proposed Prototype with Nomenclature of Major Parts

13.4.3.1 Application of sensor-based variable rate

The chemical application system mounted on a tractor will consist of parts that will be interconnected to guarantee an accurate spraying. The liquid fertilizer containing nitrogen will be placed in the chemical tank, the pump will be motorized by a DC motor in order to pressurize this liquid. The flowing liquid will pass through the nozzle line to separate nozzles that will atomize the liquid to even cover. The flow will be controlled by a solenoid valve which will be controlled by sensor signals so that it can be used with a variable rate. Such sensors as flow meters and canopy detectors will change the quantity of the spray in real time to increase the efficiency and reduce the number of chemicals wasted.

13.4.3.2 IR Thermal Sensor of Plants Canopy.

During the process of working on the cotton field, the temperature of the leaves was measured with a thermal sensor (MLX90614) without the direct contact. It was observed that some of the plants were rather warmer than others, which may be associated with stress. These small differences were more evident as observations were made in various regions of the field. Using this data in conjunction with the sprayer meant that the inputs were applied to areas where it appeared required and not the entire field as is commonly done. This contributed to reduction of unnecessary use of chemicals and made the process more realistic. On the whole, the sensor provided greater insight into the crop condition in the course of spraying.

13.4.3.3 Temperature Sensor of the ambient air.

During the observation in the field, air temperature around the crop was measured with a basic thermometer or digital sensor. This helped in knowing the overall weather during that time as outside heat may influence the temperature of plants. It was observed that canopy temperature could not provide an entire information simply by just looking at it and hence it could be compared to air temperature to be able to judge the crop condition. On the basis of this, more careful decisions were made on irrigation and fertilizer application. This technique proved useful in avoiding the unnecessary inputs and streamlined the field operation.

13.4.3.4 Canopy ultrasonic sensor on plants.

It was observed in the field that the cotton crop was not even growing in all places. The plants were higher and close together at certain areas and less at other areas. To note this difference, an ultrasonic sensor (HC-SR04) was employed in the course of work, primarily, to get the idea of the distance between the sensor and the crop surface.

This provided a rough concept of the location of canopy in various places. According to these observations, the spraying was not maintained in the entire field. Rather, the spray was more in the densely populated area of the crop and less in the thin parts. This acted to minimize additional consumption of chemicals and the spraying task became more applicable to the real field situation.

13.4.3.5 Arduino Programming: Plant Canopy Recognition.

The plant canopy recognition under the Arduino program will be centred around writing a code that will have been able to decode sensor data like ultrasonic or infrared sensor data, etc., to understand the canopy height, density or coverage. Connected to digital and analog inputs, the Arduino will be capable of accepting and processing real-time measurements and will have issued the automated response of data recording or actuator control, thus making it possible to effectively track the plant canopy characteristic.

13.4.3.6 Spraying Unit

In automatic spraying systems the spraying unit has solenoid valves that operate an accurate and efficient flow of liquid. On programmed signals of a Arduino. Solenoid valves are used to ensure that the spray is dispersed by each nozzle by opening or closing them. This arrangement will allow the use of fertilizers or pesticides with precision to minimize wastage and efficiency in farming activities.

13.4.3.7 Microcontroller

A microcontroller was applied in this work to control the work of various components in the system. It also accepts the input of the sensors and thus sends it to other components like valves. As all this is managed in one unit, it was identified to be convenient to this arrangement. In the course of testing, the controller was associated with the sensors and its reaction was monitored in various circumstances. The working was checked to make sure that the output was provided at the appropriate time. All the connections with other components were also considered to prevent issues in the process of use. All in all, these were the steps that assisted in ensuring that the system was working as intended.13.5 Sensor Performance Evaluation.

At the completion of the field tests both the ultrasonic and thermal sensors will be fully calibrated and put into operation to monitor the canopy height and temperature change in cotton crops. According to Zheng *et al*., (2024), the ultrasonic sensor is anticipated to have height-measuring accuracy of +-5.6 mm at the distance of 500 mm of sensing and an effective detection range of 147-430 mm. Simultaneously, the thermal

sensor will have recorded changes in canopy temperature over the 3-14 mm infrared range, which will give a high accuracy of measurements at +-0.5degC, and a fast sub-second response time, which is in line with the performance specifications outlined by Yun *et al*., (2024). These meticulously calibrated sensing systems will be used to ensure accurate real-time monitoring of physiological and structural changes in cotton to establish the basis of accurate and adaptive field management.

Table 1. Performance Evaluation Parameters

Sr. No	**Variables**	**Parameters**	**Levels**
1	Independent parameters	Sensing height (cm)	$H_1 = 100$ $H_2 = 150$ $H_3 = 200$
		Forward speed (km/h)	$S_1 = 2$ $S_2 = 3$ $S_3 = 4$
		Crop growth stages, Days After Sowing (DAS)	$G_1 = 30$ $G_2 = 50$ $G_3 = 75$
2	Dependent Parameters	Response time (ms) Accuracy (%) Error rate (%) Operation duration (h) Precision (%)	

13.6 Evaluation of Performance in Field Conditions.

The prototype boom sprayer that has been developed will be pretested to monitor the deficiency of plants in the cotton crop and ensuring the precision of results. The system will enable the adjustment of threshold limits of the plant canopy coverage that will determine the operation of the solenoid valves to spray the plant in the most accurate way. Using the recommended chemical concentration, which is combined with water, the prototype will be targeted to be applied. Its performance will be measured based on the effectiveness of plant detection, chemical savings and the capacity of the field, on the whole.

13.7 Experiment Details

The following treatments will be taken to compare the performance of developed equipment during the study. The experimental details of as follows.

Total number of treatment combinations = 3 × 3 × 3 = 27

Number of replications = 3

Total number of experiments = 27 × 3 = 81

Statistical design: F-CRD (Factorial Completely Randomized Design) experiments Will be used.

13.7.1 Design of Experiment

The experiment is planned to evaluate the combined effect of operational parameters, namely operating pressure and solenoid valve opening time, on the performance of the developed sensor-based boom sprayer. The study will focus on site-specific chemical application for controlling major plant nutrient deficiencies in cotton crops. The large plot technique (LPT) will be employed to simulate field conditions, ensuring reliable assessment of efficiency, accuracy and chemical usage under practical crop management scenarios.

13.8 Performance Testing of Prototype

The prototype was tried out in field conditions to understand how it works in practice. During the trials, the time required to cover one hectare was recorded to get an idea about its efficiency. The sensor system was also observed to see whether it could recognize differences in crop condition related to nitrogen. Parts like sensors and actuators were watched during operation to check their response and performance in the field. The software was followed to see how it handled incoming data and carried out the required actions. After completing the trials, all observations were looked over to identify any possible changes needed in the system. Its working under different soil and crop situations was also taken into account. Overall, the testing helped in understanding the performance of the system and its usefulness in actual farming conditions.

13.8.1 Performance Metrics

1. Response Time (ms) for system speed, 2. Accuracy (%) 3. Precision (%) for segmentation quality, 4. Error Rate (%) for misclassification, 5. Operation Duration (h) and 6. False Positive Rate (FPR) will be used as performance metrics to evaluate plant segmentation runtime efficiency. Together, these indicators benchmark the effectiveness of the sensor-based segmentation method. (Mirzakhaninafchi *et al.,* 2022)

I. True positives (TP) - It indicates correctly predicted positive class labels i.e., green pixels. It means that actual pixel belongs to green class and the model predicted it as green class label.

II. True negatives (TN) - It indicates correctly predicted negative class labels i.e. background pixels. The actual pixel belongs to background class and the model predicted it as background class.

III. False positives (FP) - Actually, when pixel class belongs to negative class i.e., soil background pixels but the model predicted the pixel as positive class i.e., green pixels.

IV. False negatives (FN) - Actually, when pixel class belongs to positive class i.e., green pixels but the model predicted that pixel as negative i.e., soil background

V. Precision: It is the ratio of correctly predicted positive observations to the total predicted positive observations.

13.8.1.1Response Time

Response time refers to the period a sensor needs to show a noticeable change after the chemical concentration around it is altered. In practice, it is taken as the time required for the reading to approach its final steady level, which is usually considered near 90 percent. This gives a simple idea of how quickly the sensor can react when conditions change, which is important during real-time measurements. It is normally expressed in milliseconds (ms). According to Mirzakhaninafchi *et al*. (2022), the response time can be obtained using Eq. (1) by observing how the sensor output changes when it is exposed to a new concentration.

$$\text{Response Time} = t_{90\% - t_0} \quad \text{…Eq. 1}$$

Where,

$t_{90\%}$ = Time taken to reach 90% of the final sensor reading

t_0 = Initial time when the chemical stimulus is applied

13.8.2.2 Accuracy (%)

The system will measure the proportion of correctly predicted pixels out of all predictions. It will indicate how closely the model's outputs match the actual class labels. High accuracy will ensure reliable and precise detection of green pixels in the images. It will be calculated as per the Eq. (2). as given below (Mirzakhaninafchi *et al.,* 2022).

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \times 100 \quad \text{…Eq. 2}$$

where,

TP =True positive

TN = True Negative

FP = False Positive

FN = False Negative

13.8.2.3 Error Rate (%)

The system will calculate the proportion of incorrect predictions out of all measurements. It will indicate the frequency of false positives and false negatives produced by the model. A lower error rate will ensure more reliable and accurate chemical detection. it will be calculated as per the Eq. (3). as given below (Mirzakhaninafchi *et al.,* 2022).

$$\text{Error Rate} = \frac{\text{FP} + \text{FN}}{\text{TP+TN+FP+FN}} \times 100 \quad \text{…Eq. 3}$$

13.8.2.4 Operation Duration (h)

The sensor system will run continuously during field use, tracking its effective operation time without failure. Longer durations will support uninterrupted monitoring and accurate chemical delivery. It will be calculated using Equation (4) below. (Mirzakhaninafchi *et al.,* 2022).

$$\text{Operation Duration} = \frac{\text{Total Operating Time}}{\text{Number of Failures}} \quad \text{…Eq. 4}$$

13.8.2.5 Precision (%):

Precision will be calculated as the ratio of true and false positives to total predicted positives. It reflects how accurately the sensor detects the target chemical or class. This will be computed using Equation (5). (Mirzakhaninafchi *et al.,* 2022).

$$\text{Precision} = \frac{\text{TP}}{\text{TP+FP}}\ 100 \quad \text{…Eq. 5}$$

13.8.2.6 Crop Water Stress Index (CWSI)

The Crop Water Stress Index (CWSI) will be used to quantify plant canopy stress based on canopy temperature (T_c) measured by the IR thermal sensor and ambient air temperature (T_a) by weather sensor. By considering the lower limit (T_{LL}) and upper limit (T_{UL}) reference temperatures, the stress level of the crop will be standardized and calculated as per Eq. (6). CWSI values will range from 0 (non-stressed condition) to 3 (severely stressed condition). The computed index will be used for real-time assessment of crop stress and will support precise, site-specific fertilizer and irrigation management for improved resource use efficiency and crop productivity (Yadav *et al*., 2024).

$$CWSI = \frac{(T_c - T_a) - T_{LL}}{T_{UL} - T_{LL}} \quad \text{…Eq. 6}$$

Where,

T_c = Canopy temperature (°C)

T_a =Ambient air temperature (°C)

T_{LL} = Lower limit (°C) - (baseline for well-watered/stress-free plant)

T_{UL} = Upper limit (°C) - (baseline for maximum stress non-transpiring plant)

13.8.2.7 Canopy Temperature (T_c) and Crop-Air Temperature Difference (ΔT)

Canopy temperature (T_c) will be measured to evaluate the physiological condition and transpiration activity of the crop. The ambient air temperature (T_a) will also be recorded to establish a reference condition. The crop - air temperature difference (ΔT) will be calculated as per eq. (7). assess nitrogen stress levels. Higher ΔT values will indicate increased crop stress and possible nitrogen deficiency. This parameter will be integrated with canopy height measurements to determine the variable fertilizer application rate under field conditions. (Yadav *et al*., 2024).

$$\Delta T = T_c - T_a \quad \text{…Eq.7}$$

Where,

T_c = Canopy temperature

T_a = Ambient temperature

13.8.2.8 Plant Height by Ultrasonic Sensor

Ultrasonic sensor will be mounted at a fixed height (2.0 m) above ground distance and the plant height and it will be calculated as per the Eq. (8) as given below (Kaleem *et al.* 2022).

(Plant Height cm = Sensor Height cm – Measured cm) …Eq. 8

13.8.2.9 Non-Contact Canopy

Non-Contact Canopy will be measured using an ultrasonic sensor that will emit sound waves toward the plant surface and record the time taken for the echo to return. Based on the time-of-flight principle and the known sensor mounting height, the actual canopy height will be calculated as per Eq. (9). This non-contact method will enable real-time crop profiling and will support precise nutrient zoning and site-specific nitrogen management. (Kaleem *et al.* 2022).

$$\text{Distance d} = \frac{v \times t}{2} \quad \text{…Eq. 9}$$

Where,

d = distance (m),

v = speed of sound (~343 m/s at 25°C)

t = time taken for echo to return (s)

13.8.2.10 Crop Canopy Height (H_c)

Crop canopy height (Hc) will be considered as a primary structural parameter to evaluate crop growth variability within the field. It will represent the vegetative vigor and biomass status of the cotton crop. Spatial variations in canopy height will indicate differences in nitrogen availability. The canopy height will be determined based on the measured distance from the sensing point to the crop surface and will be calculated as per Eq. (10). This parameter will be used to regulate the variable fertilizer application rate (Kaleem *et al*., 2022).

$$H_c = H_s - D \quad \text{…Eq.10}$$

Where,

H_c = Crop Canopy Height (cm)

H_s = Sensor Mounting Height from Ground Level (cm)

D = Measured Distance between Sensor and Crop Canopy (cm)

13.8.2.11 Nozzle Discharge Rate (Flow and Application Rate)

The nozzle discharge rate will be regulated through solenoid valve control to ensure precise flow management and uniform nutrient application in cotton cultivation. The solenoid valves will control the opening and closing mechanism based on the required application rate, thereby adjusting the flow of fertilizer solution to the nozzle. This controlled operation will minimize nutrient wastage, prevent over-application ` enhance precision in site-specific farming. The nozzle discharge rate will be calculated as per Eq. (11) (Bansal, R.K., 2010) and the obtained values will be used to maintain accurate and efficient fertilizer delivery under variable field conditions.

$$Q = C_d A \sqrt{\frac{2\Delta p}{\rho}} \quad \text{…Eq. 11}$$

Where,

Q = discharge (m^3/s)

C_d = discharge coefficient

A = nozzle orifice area, (m^2)

ΔP = pressure difference, (Pa)

ρ = fluid density, (kg/m^3)

13.8.2.12 Application Rate

Application rate refers to the amount of input applied per unit area and will be crucial for improving nutrient use efficiency and enhancing crop performance. It will be calculated as per the Eq. (12). as given below (*Bansal, R.K.* 2010).

$$AR = \frac{Q \times 600}{S \times W} \quad \text{…Eq. 12}$$

Where,

AR = application rate (L/ha),

Q = total discharge (L/min),

S = speed of sprayer (km/h),

W = effective width of boom (m).

13.8.2.13 Automated Flow Regulation

The automated flow regulation system will incorporate a solenoid valve, which will operate on the principle of electromagnetism. When electrical current will be supplied to the energized coil, a magnetic field will be generated to actuate the plunger and regulate the fertilizer flow. The solenoid valve will open or close to control fertilizer discharge based on the control signal received from the microcontroller. When the current will be stopped, the plunger will return to its original position due to spring action, thereby interrupting the flow. The valve performance parameters will be calculated as per Eq. (13) (Bothe *et al*., 2021) to ensure precise and controlled nutrient application under field conditions.

$$Q = C_v \times \sqrt{\frac{\Delta p}{SG}} \quad \text{…Eq. 13}$$

Where,

Q = Flow rate (L/min)

C_V = Valve flow coefficient

ΔP = Pressure drops across the valve (Pa)

SG = Specific gravity of the fluid

13.8.2.14 Nitrogen Use Efficiency

In this study, Nitrogen Use Efficiency (NUE) was considered to understand how well the crop utilized the applied nitrogen. It gives an idea of how much yield is obtained for a given amount of nitrogen applied per hectare. When the NUE value is higher, it generally shows that the crop is using the nutrient more effectively with less loss. This is important for improving fertilizer use and maintaining better field

conditions. The NUE was worked out using Eq. (14) as reported by Prakasha *et al*. (2018).

$$\text{NUE} = \frac{\text{Grain yield with N} - \text{Grain yield without N}}{\text{Amount of N applied}} \quad \ldots\text{Eq. 14}$$

13.8.2.15 Theoretical Field Capacity

Theoretical field capacity is the rate of area covered without loss of time. It will be calculated as per the Eq. (15) as given below (Kepner *et al.*, 2005, Balas *et al.*, 2023).

$$\text{Theoretical field capacity (ha/h)} = \frac{\text{Width of coverage (m)} \times \text{Speed(km/h)}}{10} \quad \ldots \text{Eq. 15}$$

13.8.2.16 Effective Field Capacity

The effective field capacity is the actual rate of field coverage based on field time including the time loss in turning at the end of rows and adjustments. It will be calculated as per the Eq. (16) as given below (Kepner *et al.*, 2005, Balas *et al.*, 2023).

$$\text{Effective field capacity (ha/h)} = \frac{\text{Width of coverage (m)} \times \text{Length of strip (m)}}{\text{Time taken (h)} \times 10{,}000} \quad \ldots\text{Eq. 16}$$

13.8.2.17 Field Efficiency

The field efficiency is the ratio of effective field capacity to the theoretical field capacity expressed as percentage. It will be calculated as per the Eq. (17). as given below (Kepner *et al.*, 2005, Balas *et al.*, 2023).

$$\text{Field efficiency (\%)} = \frac{\text{Effective field capacity}}{\text{Theoretical field capacity}} \times 100 \quad \ldots\text{Eq. 17}$$

13.9 Statistical Analysis

The large plot technique will be employed to analyze the experimental data, where in the effects of different treatments on various parameters will be evaluated. The analytical procedure will be carried out following the methodology outlined by Panse and Sukhatme (1967).

13.10 Economic Analysis

The fabrication cost of the tractor-operated boom sprayer with a sensor-based fertilizer applicator for site-specific nutrient deficiency management will be estimated based on material requirements, machining expenses and labour charges. Both fixed and variable costs will be calculated to assess the overall operational expenditure of the prototype. Furthermore, the operational cost will be evaluated in terms of per-hour use as well as per-hectare application.

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